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HIGH-PRECISION RELATIVE EVENT LOCATION WITH CROSS-SPECTRAL ANALYSIS

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Location relative to a reference event is often more useful and precise than absolute event location. The use of relative location accounts for most of the errors arising from path effects. Such location requires relative times for pairs of events observed at a common station, which can be obtained with high precision for similar events by waveform cross-correlation. The precision can be further boosted by applying the cross-spectral analysis method, which can obtain relative delay times with resolution up to an order magnitude better than the seismogram sampling interval. During this report period, records of a large number of explosions with precisely known locations were assembled. Software for determining the delay time between two waveforms was developed and tested on real data. Preliminary analysis of data from six closely-located Yucca Flat explosions recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV provided encouraging results. The mean location error was found to be only about 1 km; an impressive result if one considers the large epicentral distances (about 200 km to 320 km) and the complex geology of the Nevada Test Site.

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1. SUMMARY

Location relative to a reference event is often more useful and precise than absolute event location. The use of relative location accounts for most of the errors arising from path effects. Such location requires relative times for pairs of events observed at a common station, which can be obtained with high precision for similar events by waveform cross-correlation.

The precision can be further boosted by applying the cross-spectral analysis method, which can obtain relative delay times with resolution up to an order of magnitude better than the seismogram sampling interval. In the cross-spectral analysis method, the delay time is simply the slope of the phase of the cross-spectrum. This is obtained by fitting a slope through 0, using a weighting scheme based on the coherence of the cross-spectrum.

During this report period, records of a large number of explosions with precisely known locations were assembled. Software for determining the delay time between two waveforms was developed and tested on real data. Preliminary analysis of data from six closely-located Yucca Flat explosions recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV provided encouraging results. The relative arrival times between two closely spaced explosions recorded at a common station were determined with a precision of 0.001 sec. The mean location error was found to be only about 1 km; an impressive result if one considers the large epicentral distances (about 200 km to 320 km) and the complex geology of the Nevada Test Site.

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2. INTRODUCTION

One of the most important tasks in monitoring underground nuclear tests is the simple location of regional events. In fact, the location itself is often useful for discriminating between explosions and earthquakes. Location techniques generally rely on travel times and back azimuths recorded at several stations, using some variant on Geiger's classic inversion algorithm (*e. g.*, Aki and Richards, 1980). The main cause of errors in such location algorithms is poorly known earth structure models or three-dimensional variations in velocity. While these effects tend to be averaged out if enough stations are used, locations using small numbers of stations can have large errors. However, in many cases, a location relative to a reference event is sufficient. The most common use of relative location in seismology is locating aftershocks relative to the main shock. This is useful because the smaller events are are observed at fewer stations and thus their locations are affected more by earth structure. Relative relocation has the advantage of canceling out the major portion of the path effect, if the event is close enough to the reference event.

Another case where relative location can be useful is in locating an event whose absolute location is near a known mine or quarry, or near a known nuclear testing site. In this case, the probability that a given event occurred within a mine or test site could be established with greater certainty than with an absolute location by locating the event relative to a reference event known to have occurred at the mine or test site. Relative location can also improve the locations of nuclear tests, particularly if the absolute location of a reference event can be established using satellite imagery.

In conventional relative event location, events are located relative to a reference event by using time differences for a given arrival measured for both the reference event and the other

events. Lynnes and Ruff (1985) made a comparison of thc ISC spatial locations of an aftershock sequence for an earthquake in the North Atlantic and relative locations based only on differences between aftershock and main shock P wave arrival times. Despite the fact that many of the events were recorded by as few as three stations, the relative location method produced locations aligned along the fault plane.

3. CROSS-SPECTRAL ANALYSIS

Relative locations are limited primarily by the precision with which the phase arrival times can be measured. For two events that occur close together, the waveforms are often similar. In such cases a cross-correlation of an event's waveforms can provide much improved estimates of the relative times, since the full waveform is used rather than a subjective pick of the initial phase arrival. Conventional cross-correlation slides one waveform past another, and the lag with the optimum correlation coefficient is taken as the relative time. However, the cross-spectral analysis method can yield improved relative time estimates. Following Ito (1985), the cross-spectrum, Sc(f), of two signals A and B is:

$$Sc(f) = \frac{F_a(f)\, F^*{}_b(f)}{T} = Re(f) - i\, Im(f), \tag{1}$$

where F(f) is the Fourier transform of f(t) and * indicates the complex conjugate. Then the phase spectrum $\phi(f)$ is

$$\phi(f) = \tan^{-1} \frac{-Im(f)}{Re(f)} \tag{2}$$

If the two seismograms are similar in shape but have different amplitudes, then

$$f_b(t) = k\, f_a(t+\tau), \tag{3}$$

and by the application of the shift theorem, the phase spectrum becomes

$$\phi(f) = 2\,\pi\, f\, \tau \tag{4}$$

Thus the delay time τ can be obtained by simply by fitting a straight line through the phase of the cross-spectrum with intercept 0. In fitting this slope, the values are weighted based on the coherence C(f):

$$C(f) = \frac{\left| \sum_{f'=f-\Delta f}^{f'=f+\Delta f} Sc(f') \right|}{\sum_{f'=f-\Delta f}^{f'=f+\Delta f} \sqrt{S_a(f')\, S_b(f')}} \qquad (5)$$

where S(f) is the signal power. The weighting factor, W(f) in the linear fit is based on the Hannon-Thomson processor (Knapp and Carter, 1976), *i. e.*

$$W(f) = \frac{C^2(f)}{1 - C^2(f)} \qquad (6)$$

The slope of the line has a continuum of possible values, rather than discrete values, with the result that estimates of delay time for highly coherent pairs can actually be an order of magnitude more precise than the sample rate. This technique has been applied successfully to local sequences of earthquakes with impressively precise locations. Fremont and Malone (1987) obtained precisions of 20 m for earthquakes within 250 m of each other. Ito (1985) obtained precision of 50 m for microearthquakes within about 500 m of each other.

4. PRELIMINARY RESULTS

In order to understand the influence of path differences on waveforms, records of a large number of explosions with precisely known locations have been assembled. Most of these data are at regional distances and the magnitude, m_b varies over a large range (about 3.3 to 6.2). An analysis of differences in the observed regional phases (especially Pn and Lg) from closely spaced explosions at the Nevada Test Site recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV has been started. Attempts will be made to understand the observed spectral and time-domain differences in terms of variations of inter-shot distance, shot depth, and geological environment.

Software for determining the delay time between two waveforms has been developed and tested. The relative arrival times between two events recorded at a common station are determined with a precision of 0.001 sec. Results based on use of the Yucca Flat explosions ROUSANNE and BASEBALL, assuming BASEBALL to be the shot with known location, derived from records at ELK, KNB, LAC, and MNV are shown in Figures 1, 2, 3, and 4, respectively. The geographic locations of these two shots, separated by about 2.37 km, are precisely known. The digital data are sampled at about 42 samples/sec. Figure 1 (bottom) shows the input waveforms which may be selected to be of any desired duration. The signal window over which a cosine taper applies is also variable. The top plot shows the phase of the cross-spectrum varying between -2π and $+2\pi$. The lower plot shows the coherency, varying between 0 and 1, derived by using a bandwidth of 1.0 Hz. As expected from theory (*e. g.*, Frankel and Clayton, 1986), the coherency is generally observed to decline with increasing frequency. The delay time is simply the slope of the phase of the cross-spectrum over the specified range of 0.5-5.0 Hz and is obtained by fitting a slope through 0, using a

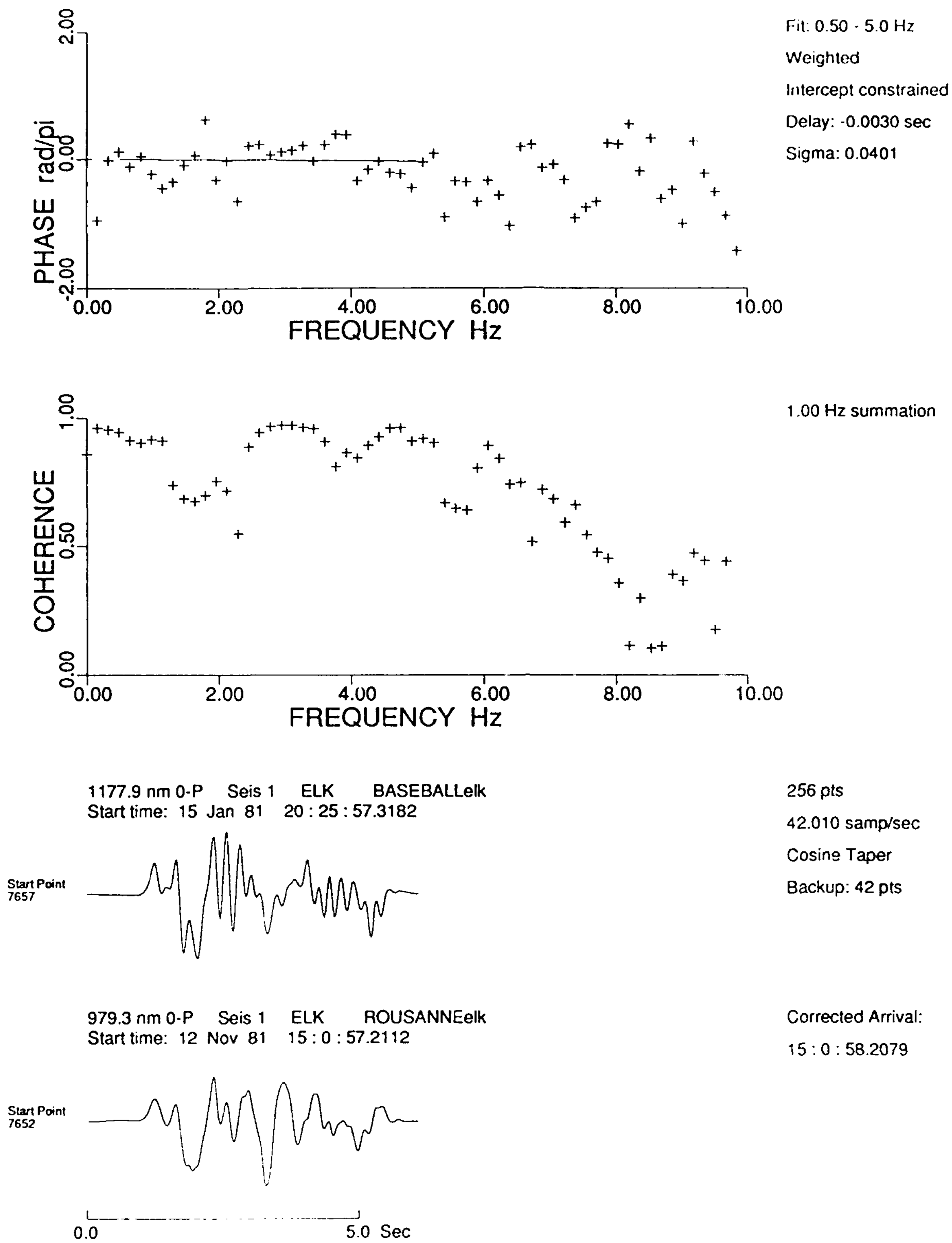

Figure 1. Cross-spectral analysis for measuring delay times. The two input waveforms (bottom), each 256 points long, provide the phase of the cross-spectrum (top) and coherence based on bandwidth of 1.0 Hz for frequencies up to 10 Hz. The slope of the phase spectrum, computed by fixing the intercept to 0 and applying weights related to the coherence, provides the delay time used to obtain the corrected arrival time for ROUSANNE recorded at ELK.

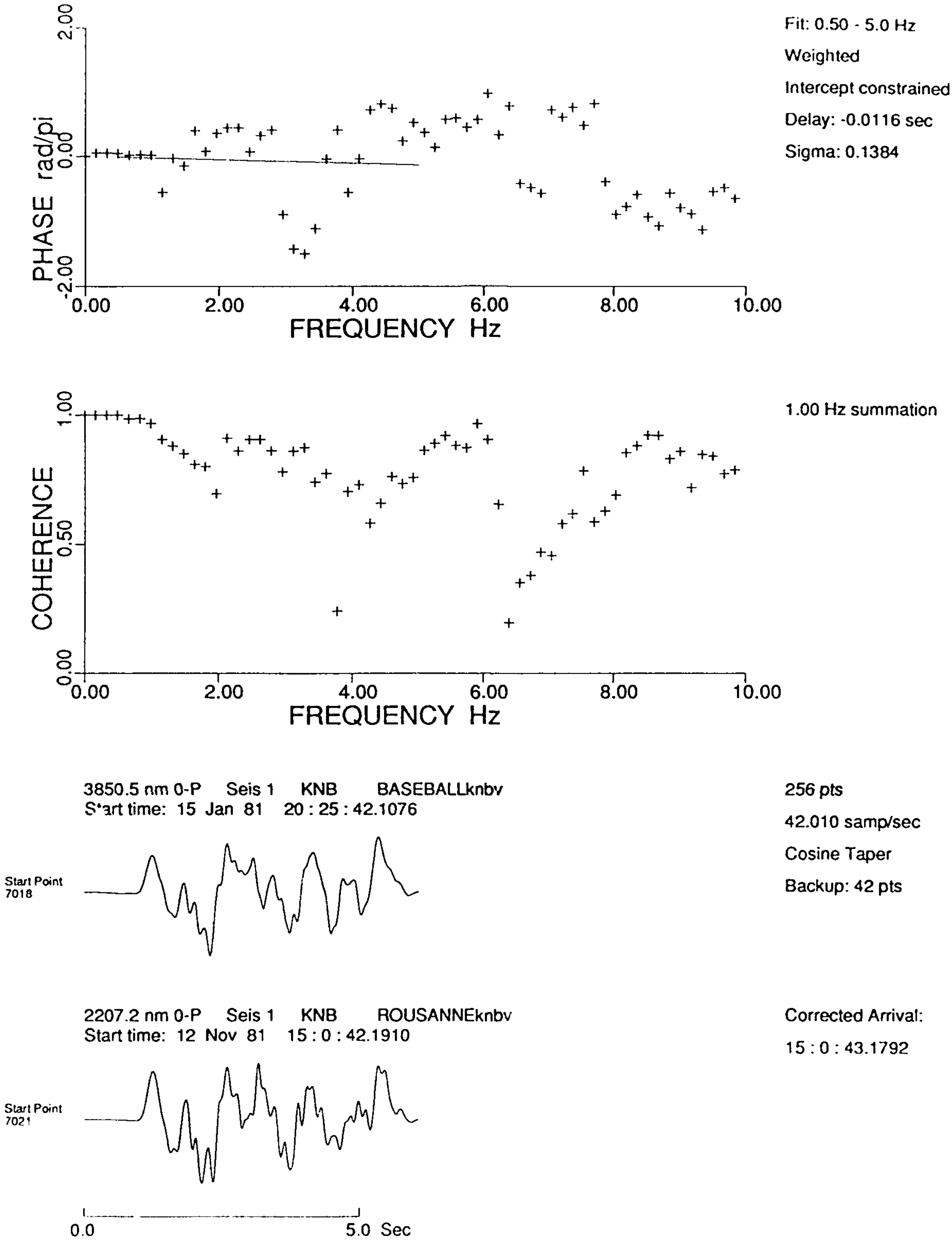

Figure 2. Similar to Figure 1 for records at KNB.

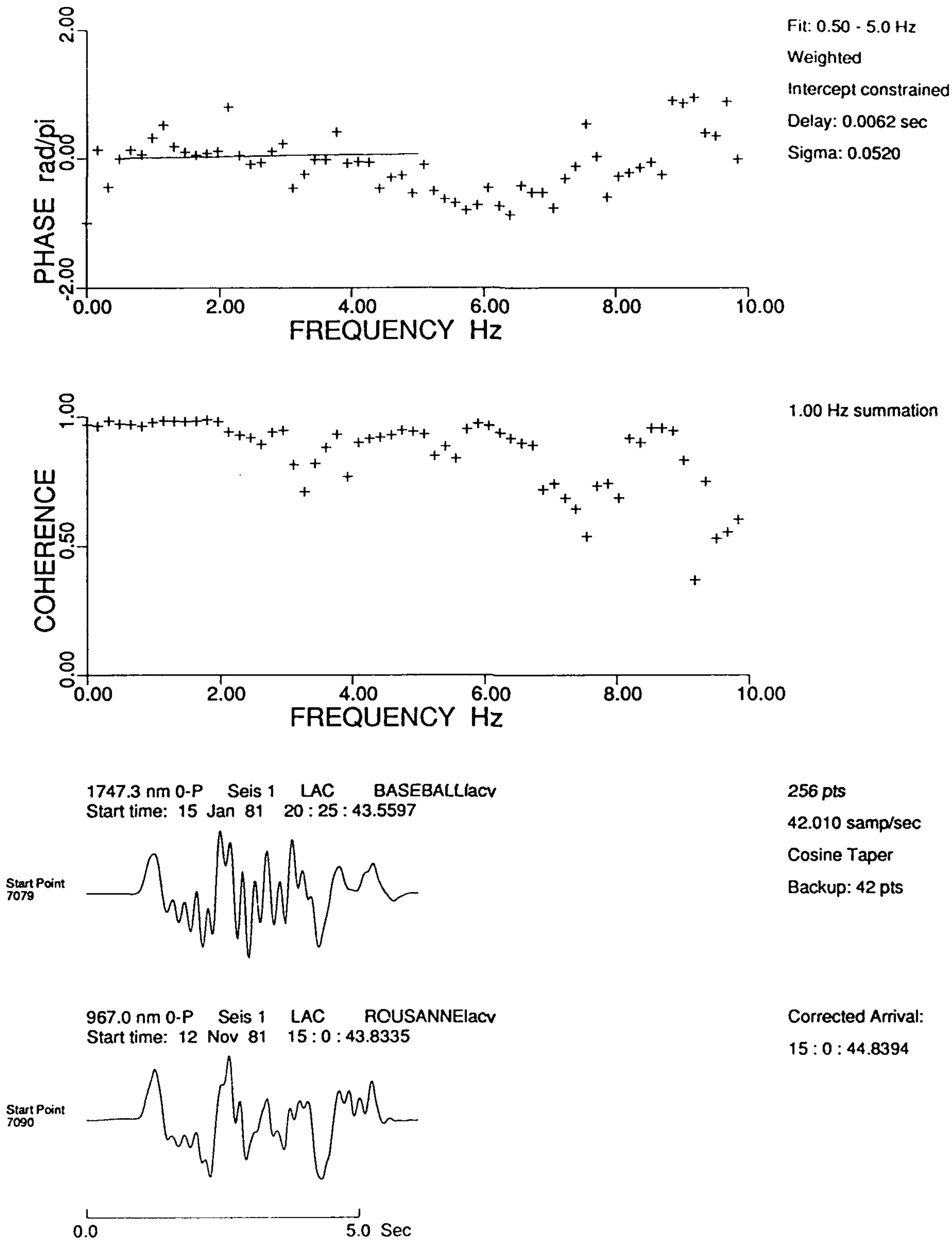

Figure 3. Similar to Figure 1 for records at LAC.

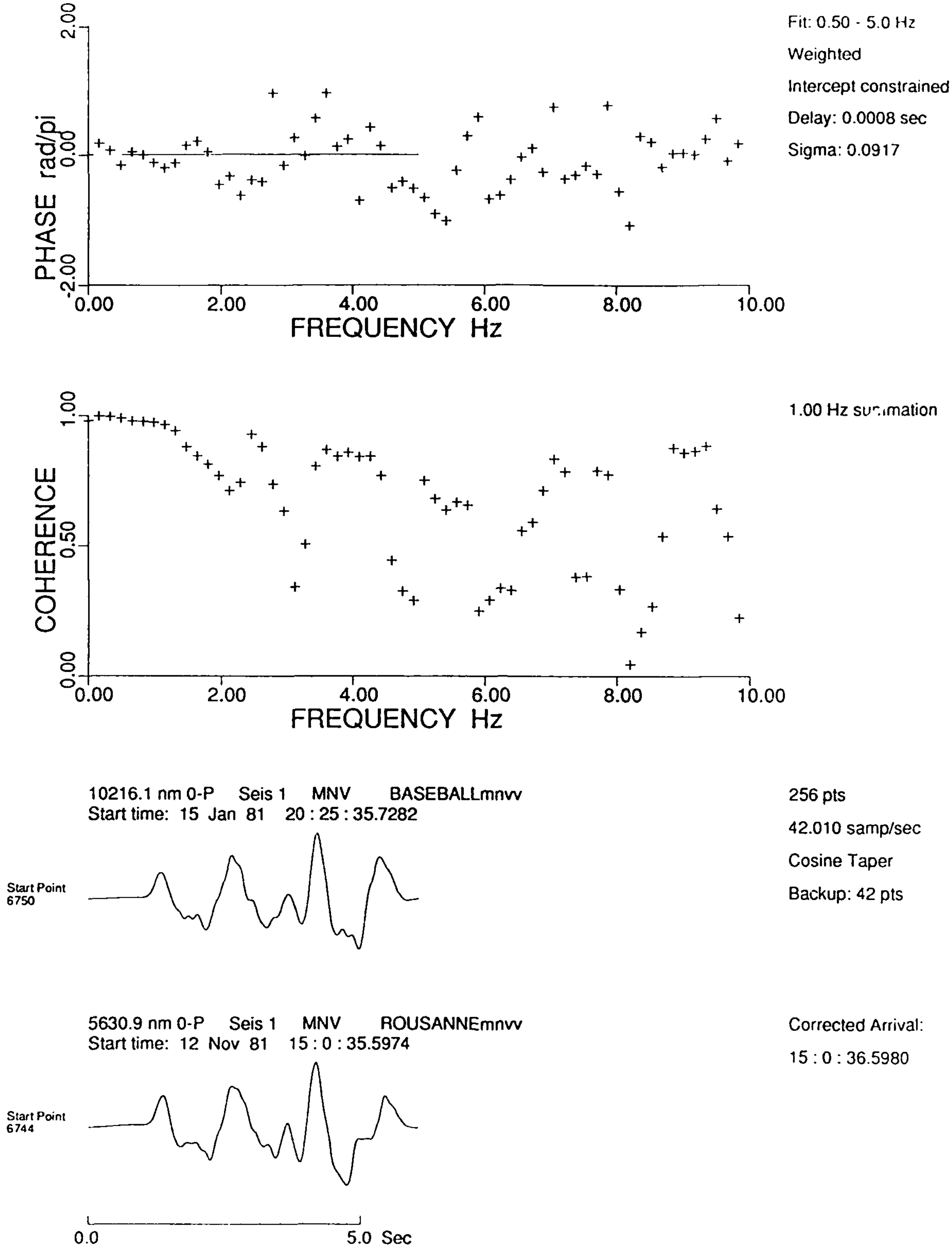

Figure 4. Similar to Figure 1 for records at MNV.

weighting scheme based on coherence of the cross-spectrum (see equation 6).

Using BASEBALL as the reference explosion, the computed arrival times (such as those indicated on Figures 1 to 4) are used as input to the LOCATE feature of the Analyst Review Station (ARS) to obtain the epicentral location and the origin time. The arrival times (without any delay correction) for BASEBALL recorded at the four stations are also used to compute the corresponding ARS location. The ARS computed locations and the actual (known) locations are given in Table 1 and also shown in Figure 5. The ARS computed locations for the five shots (paired with BASEBALL) are shifted by the amount of shift between the ARS computed and actual locations of BASEBALL. A comparison of the shifted locations of each of the five shots with its actual location provides the location error associated with each shot (Figure 5). The mean location error is only 1.22 km with one standard deviation of 0.61 km. This result appears to be impressive if one considers the large epicentral distances (about 200 km to 320 km) and the complex geology of the Nevada test site.

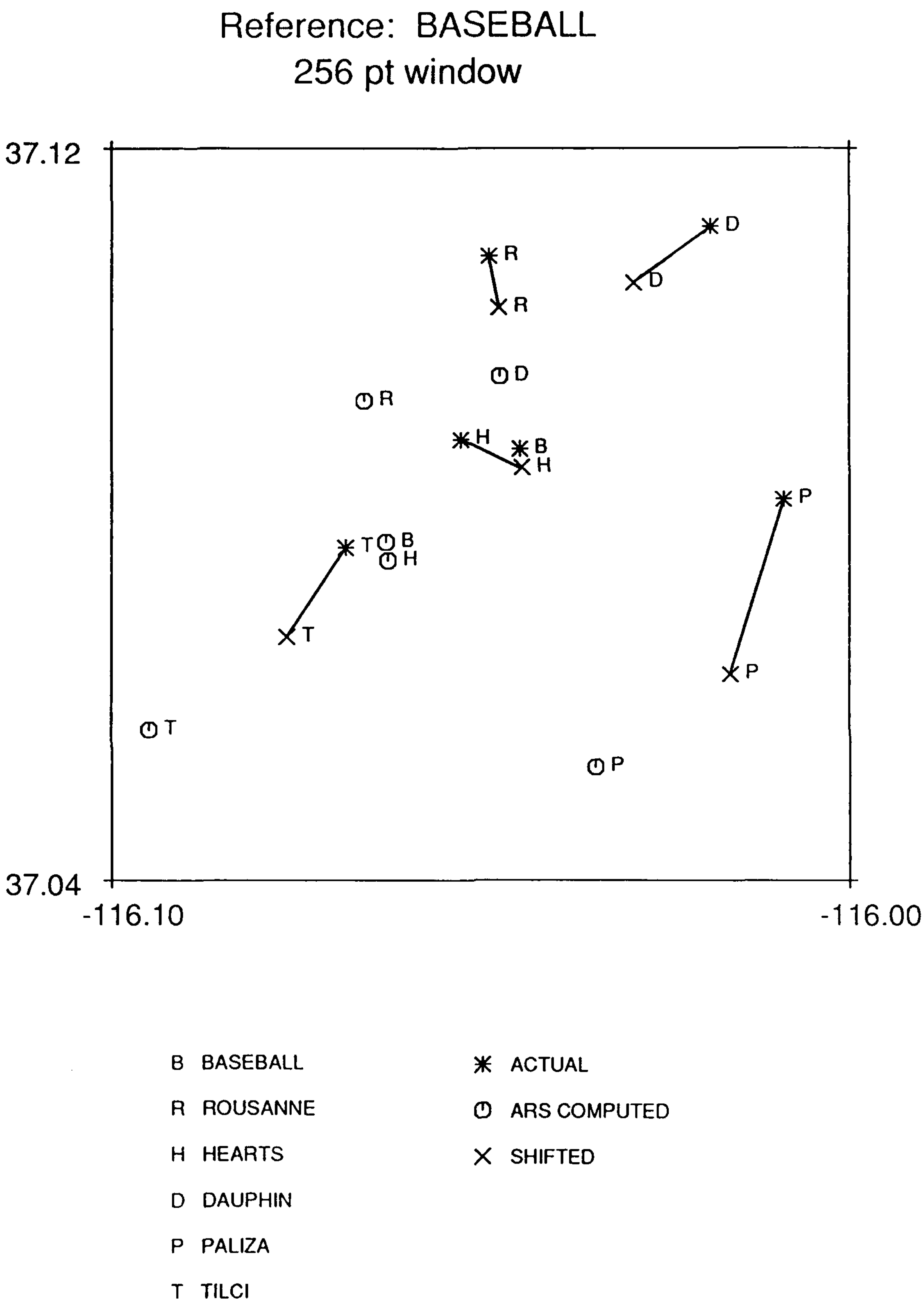

Figure 5. Map of six explosions at Yucca Flat showing the actual locations, ARS computed locations, and locations with shift based on BASEBALL. The five lines indicate the error between the actual and computed locations.

TABLE 1

CROSS-SPECTRAL ANALYSIS (SIX YUCCA FLAT SHOTS)

EVENT	ACTUAL LOCATION	COMPUTED LOCATION	SHIFTED LOCATION	SHIFTED - ACTUAL	LOCATION ERROR (km)
BASEBALL	37.0871	37.0769	37.0871	0.0000	0.000
	-116.0447	-116.0631	-116.0447	0.0000	
DAUPHIN	37.1115	37.0951	37.1053	-0.0062	1.152
	-116.0187	-116.0475	-116.0291	-0.0104	
HEARTS	37.0881	37.0749	37.0851	-0.0030	0.818
	-116.0528	-116.0628	-116.0444	0.0084	
PALIZA	37.0816	37.0523	37.0625	-0.0191	2.215
	-116.0088	-116.0344	-116.0160	-0.0072	
ROUSANNE	37.1082	37.0924	37.1026	-0.0056	0.634
	-116.0490	-116.0660	-116.0476	0.0014	
TILCI	37.0763	37.0564	37.0666	-0.0097	1.291
	-116.0685	-116.0949	-116.0765	-0.0080	

Cross spectral analysis based on the use of shorter (128 points) windows was also carried out for the same 6 explosions. Results for ROUSANNE and BASEBALL (reference shot) are shown in Figure 6, 7, 8, and 9 in which a bandwidth of 2.0 Hz is used for deriving coherency and a frequency range of 1.0-10.0 Hz is used for computing the delay time. A comparison with the earlier results (Figures 1 to 4) suggests significantly larger coherency over a much larger range of frequencies. It seems therefore that the first arrivals in Pn are considerably more similar than the later arriving phases, perhaps due to greater contamination by later-arriving scattered energy. As before, the coherency is generally observed to decline with

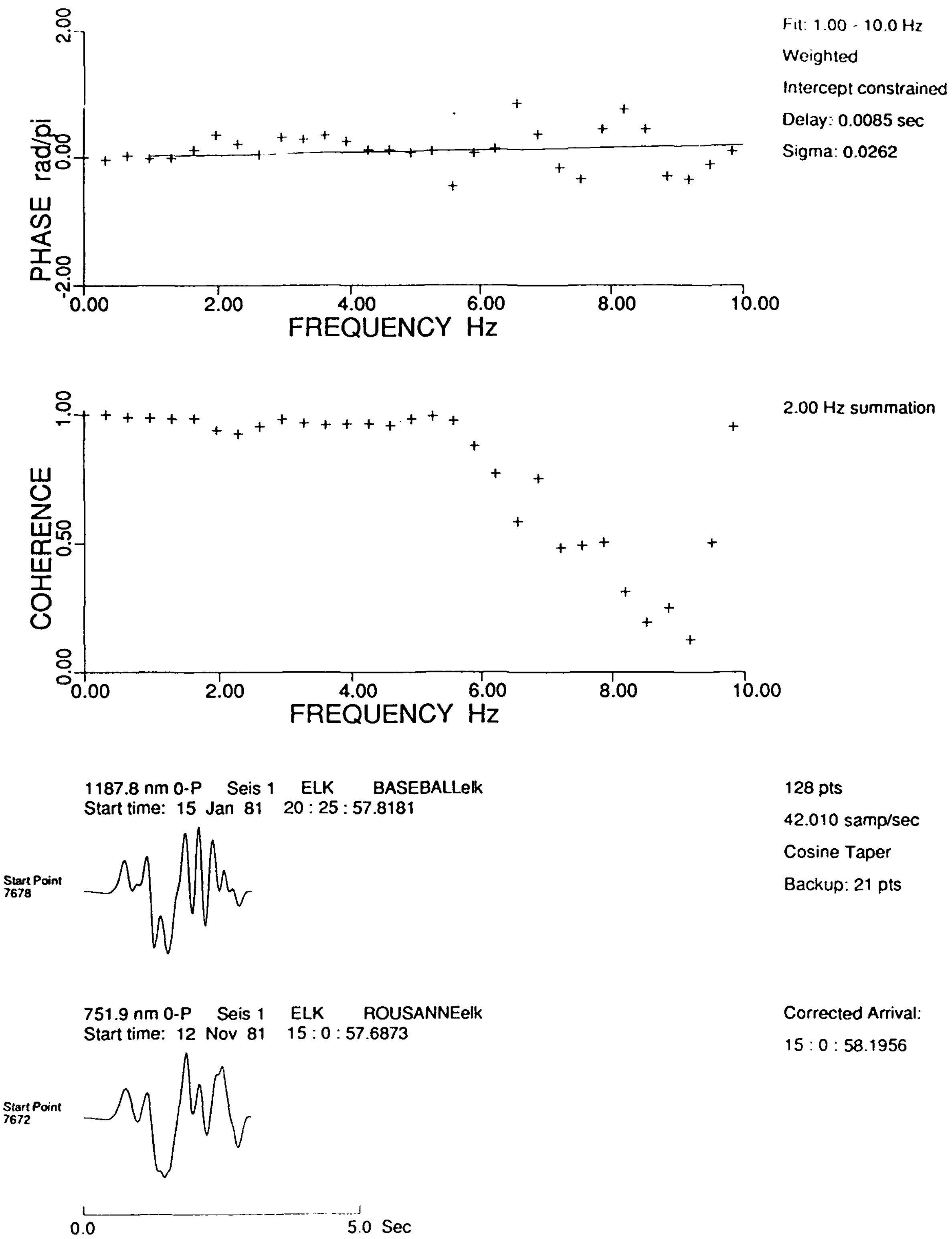

Figure 6. Similar to Figure 1 for shorter (128 points) waveforms recorded at ELK.

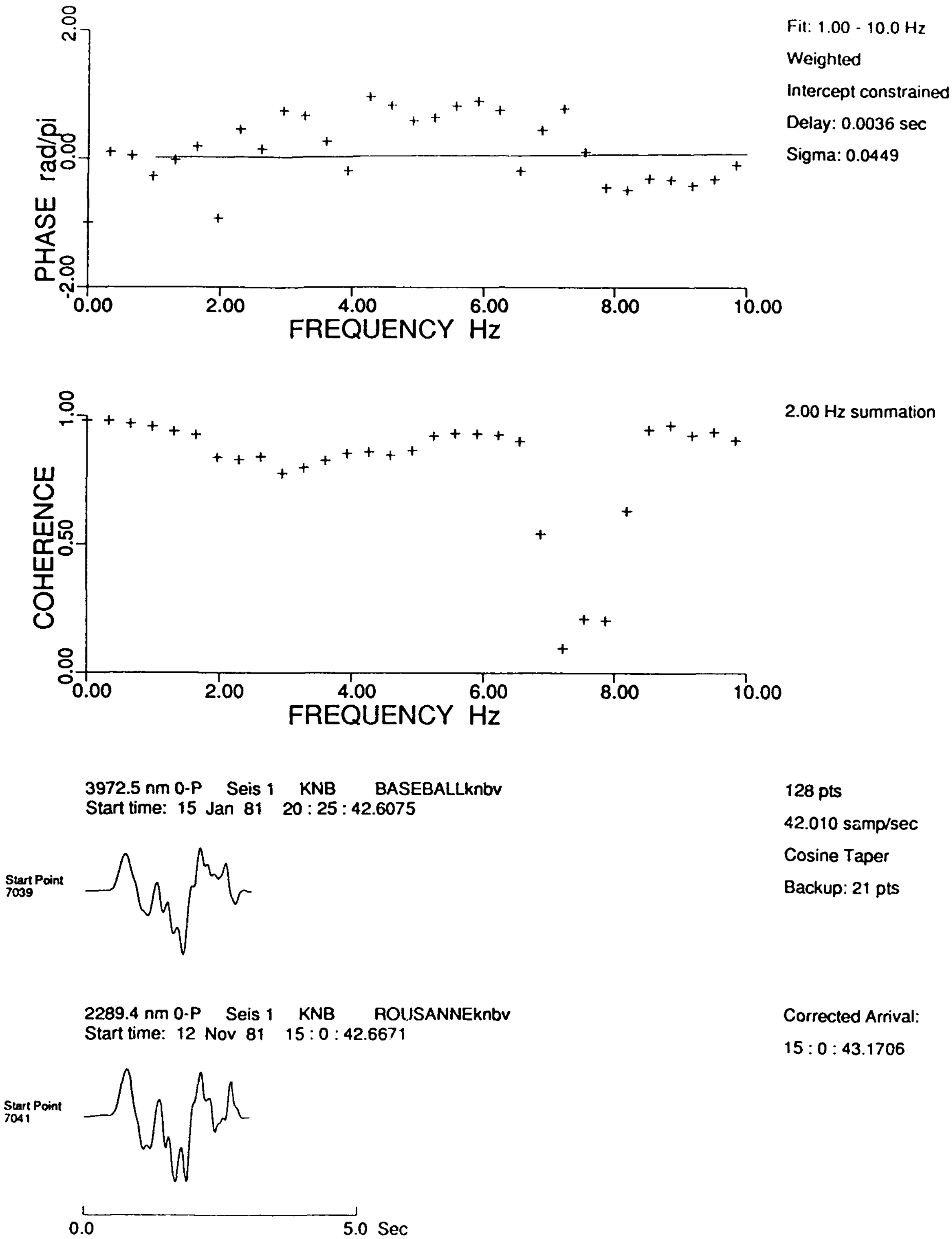

Figure 7. Similar to Figure 1 for shorter (128 points) waveforms recorded at KNB.

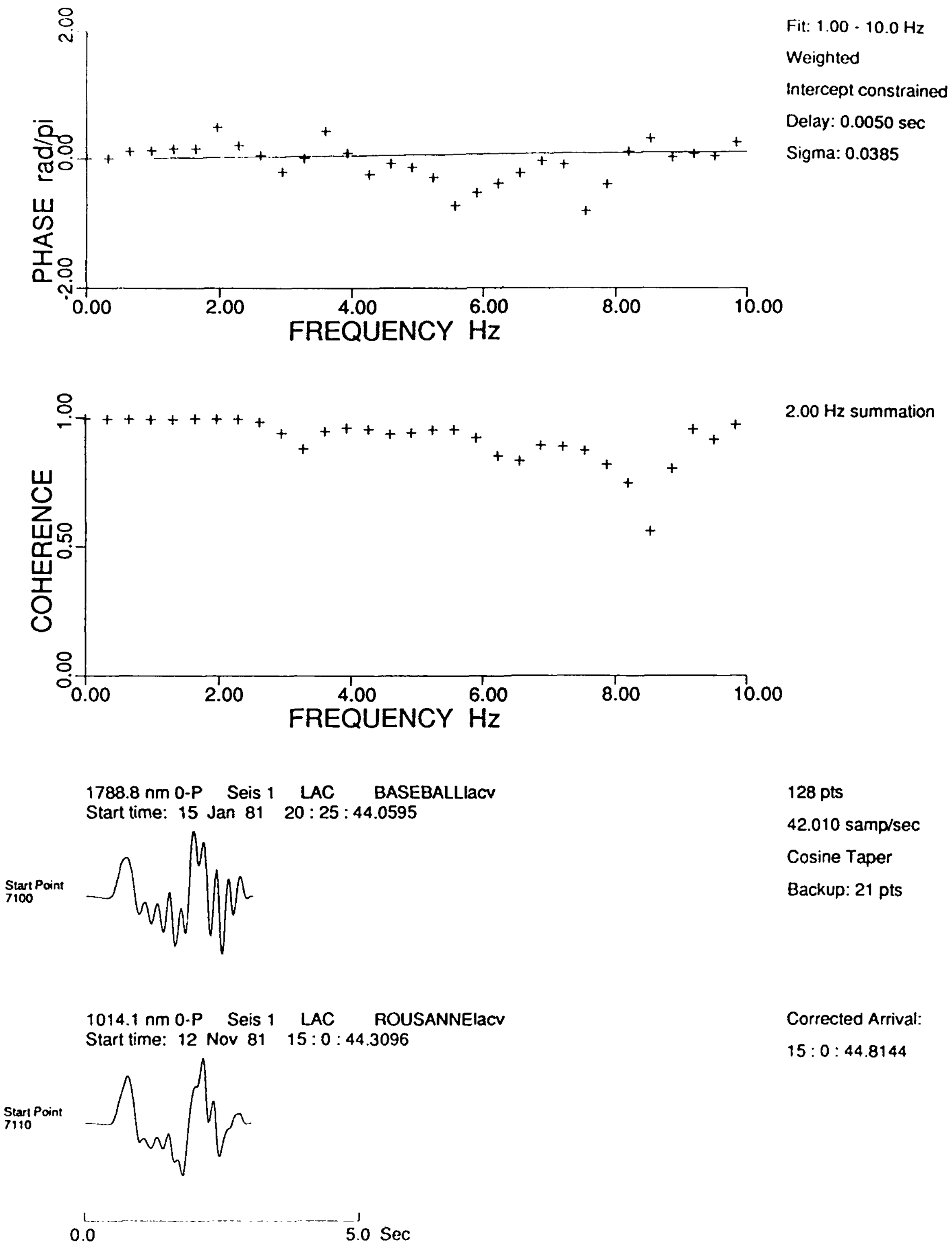

Figure 8. Similar to Figure 1 for shorter (128 points) waveforms recorded at LAC.

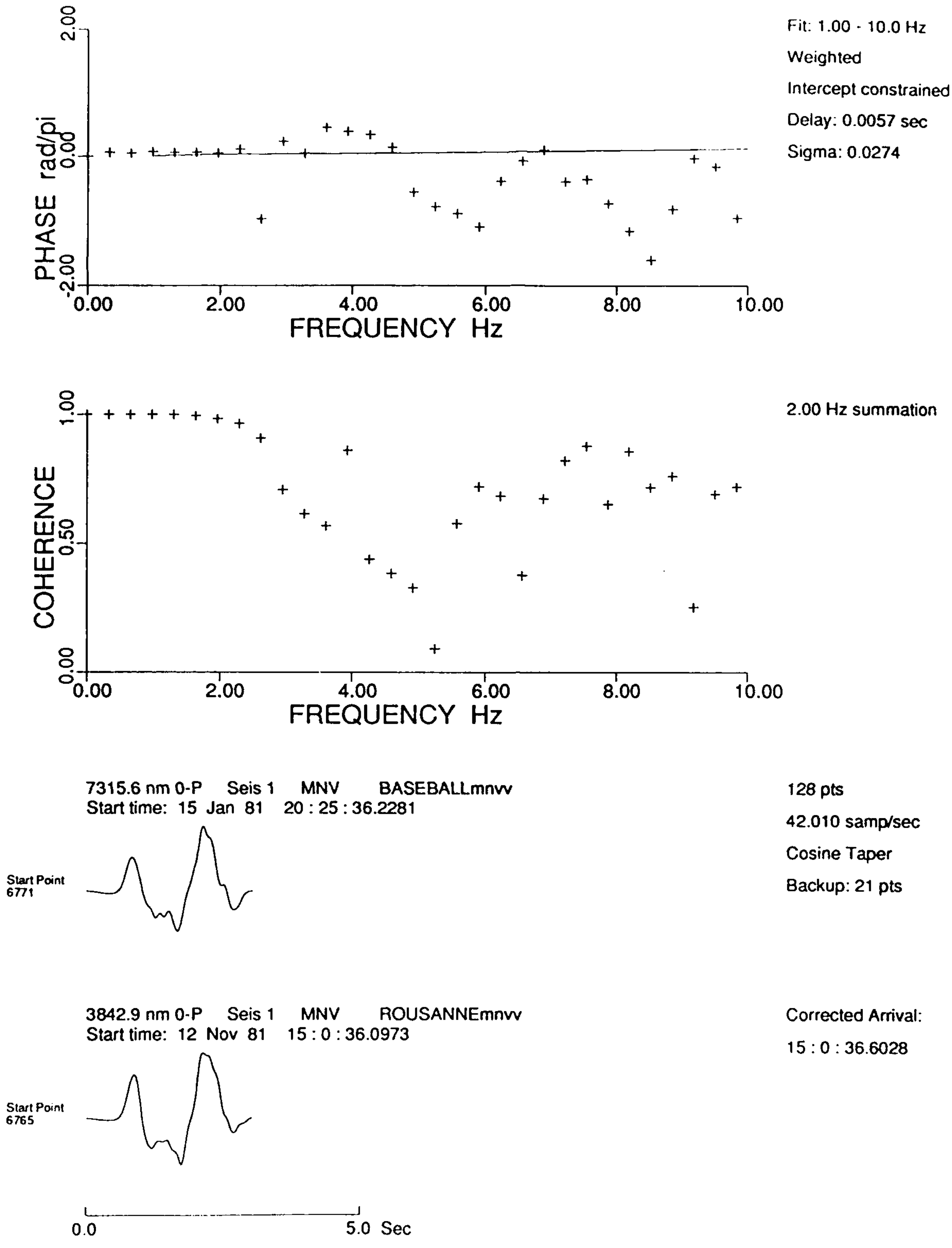

Figure 9. Similar to Figure 1 for shorter (128 points) waveforms recorded at MNV.

increasing frequency. The location results, shown in Figure 10, are very similar to those in Figure 5 in both the magnitude and azimuthal direction of the location errors. The mean location error is 1.31 km with a standard deviation of 0.62 km.

A limitation of our analysis so far has been the use of the ARS to derive absolute locations for the reference and other shots. In the future, we plan to obtain relative locations directly from differences between arrival times of the reference shot and other explosions. This may significantly improve the precision of relative locations.

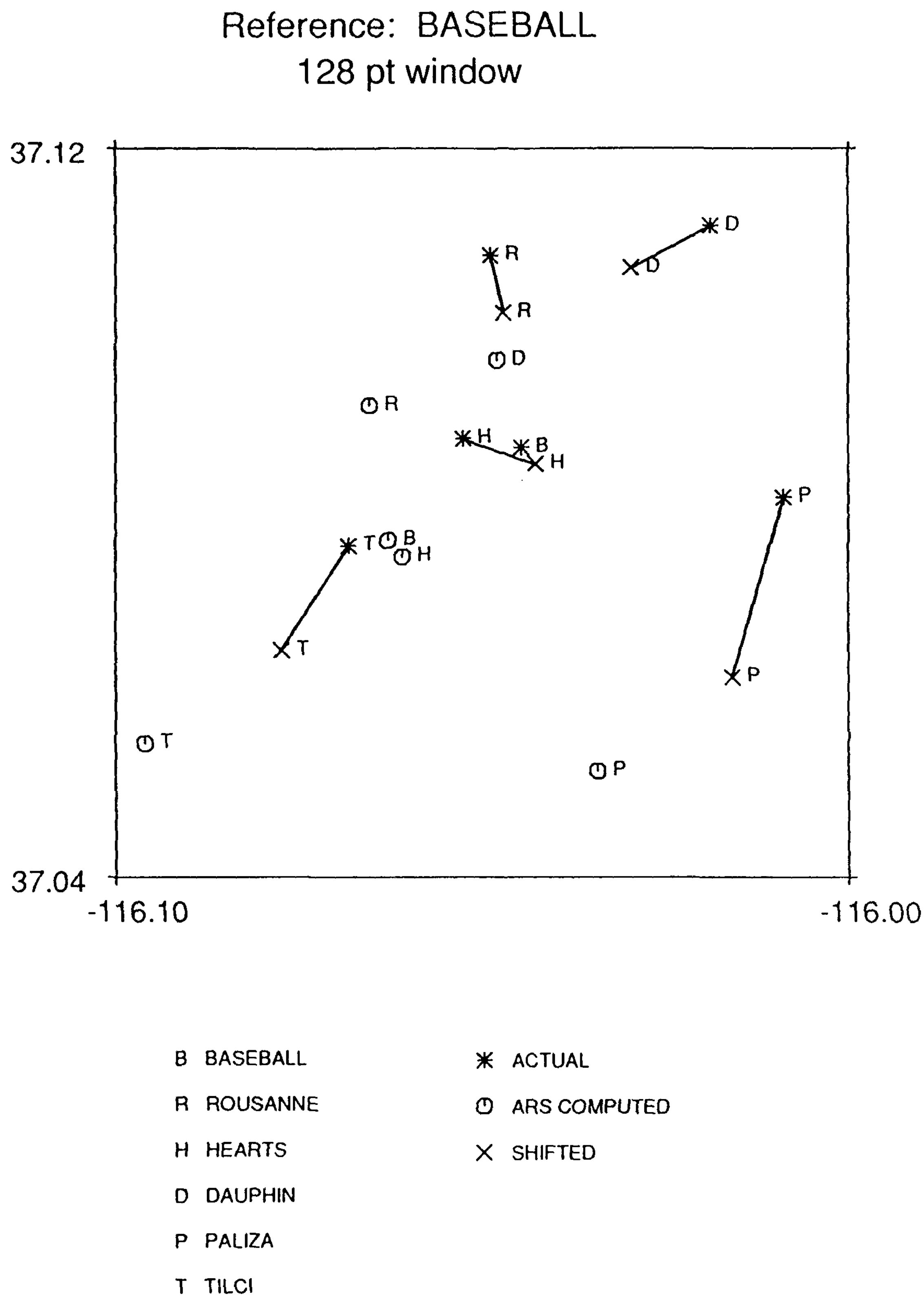

Figure 10. Similar to Figure 5 based on the use of shorter (128 points) waveforms. Note the similarity of location errors with those in Figure 5.

5. CONCLUSIONS

Good quality records of a large number of explosions with precisely known locations and reliable time channel were assembled and software for determining the delay time between two waveforms was developed and tested. Encouraging results were obtained in a preliminary analysis of data from six closely-located Yucca Flat explosions recorded at the four broadband digital stations, ELK, KNB, LAC, and MNV. The relative arrival times between two closely spaced explosions recorded at a common station were determined with a precision of 0.001 sec. Use of long and short signal windows gave nearly identical results with the mean location error of only about 1 km. This is an impressive result if one considers the large epicentral distances (about 200 km to 320 km) and the complex geology of the Nevada test site.

6. ACKNOWLEDGMENTS

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